

Concept and Implementation of a Selective Weakening Approach for the Seismic Retrofit of R.C. Buildings

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2006 NZSEE
Conference

ABSTRACT: Current seismic retrofit strategies generally focus on increasing the strength/stiffness or upgrading mechanical properties of a structure. A typical drawback with this is that the upgraded behaviour might result in an increased demand on the structural and sub-structural elements, i.e. foundation. Herein proposed is a counter-intuitive but rational seismic retrofit strategy of selectively weakening a structural system. Such a retrofit strategy is suitable for application to alternative seismic resisting systems and components including walls, beams, columns and diaphragm connections.

A selective weakening intervention is performed within an overall performance-based retrofit approach with the aim of improving the inelastic behaviour by first reducing the strength/stiffness of specific members within the structural system. This in turn results in a reduced demand on the structural member. Once weakening has been achieved the designer can use the wide range of techniques and materials available (e.g. use of fibre reinforced polymers, steel plates, jacketing or shotcrete) to ensure that adequate characteristics are achieved. Whilst performing this it has to be assured that the structure meets specific performance criteria and the principles of capacity design.

As the first phase in the development of selective weakening, the feasibility of such a retrofit strategy is discussed, with particular focus on possible applications to the seismic retrofit of existing reinforced concrete structural walls. The proposed intervention involves splitting the wall vertically and cutting it at the foundation level to change the inelastic mechanism from shear-type to a flexural/rocking-type behaviour. As part of the overall research program, a series of experimental (quasi-static cyclic) tests on 2/3 scaled reinforced concrete walls representing pre-1970 construction practice or retrofitted configurations are under preparation. A summary of the retrofit strategy design and expected behaviour will be herein given.

1 INTRODUCTION

Recent earthquake events (e.g. Turkey 1999, 2003 and Taiwan 1999) have highlighted the undesirable behaviour of some existing reinforced concrete structures and the need for appropriate retrofit solutions. Currently two alternative approaches for seismic retrofit are conceptually adopted and implemented in practice: the first approach focuses on reducing earthquake induced forces (i.e. modifying the demand) and the second focuses on upgrading the structure to resist earthquake induced forces (i.e. modifying the capacity, Chuang and Zhuge 2005). In order to reduce earthquake induced forces, base isolation or damping devices are commonly added to the structure, whilst upgrading of the structural capacity is usually achieved by intervening on specific elements or by changing the load paths within the structure. A wide variety of different retrofit techniques for existing reinforced concrete structures including the use of advanced materials (i.e. Fibre Reinforced Polymers) have been extensively investigated and successfully implemented. Issues related to costs, invasiveness and the requirement of specialist knowledge are however typical problems encountered. A comprehensive summary can be found in fib bulletin on seismic retrofit (2003a) and on FRP (2001), while some specific approaches will be mentioned in a later section.

This paper defines and introduces the concepts for an alternative seismic retrofit strategy referred to as a “selective weakening” approach (Pampanin, 2005b) which focuses on protecting undesirable seismic response mechanisms by first strategically weakening specific elements within a structure. Weakening a structure will reduce the seismic demand while at the same time changing the inelastic mechanism according to capacity design principles in order to achieve an overall higher performance level. In a second phase, to achieve a complete retrofit solution other currently available and applicable retrofit techniques can be used in combination with the selective weakening strategy to upgrade the weakened structure to the desired and controlled level of capacity. Recent developments in building technology and high-performance seismic-resisting systems (fib 2003b; Pampanin, 2005a), focusing on the use of a rocking response to ensure minimal damage and to achieve a self-centring behaviour (negligible residual displacements), can for example suggest proper implementation of a selective weakening strategy to existing buildings, whereby the obtained rocking motion is combined with additional dissipation/damping properties for a low level of post-earthquake damage.

The first stage of an ongoing research project which is focusing on investigating/developing selective weakening is underway in the form of experimental and analytical investigations for the application to structural walls. It can be easily anticipated that the selective weakening approach is not limited for the retrofit of structural walls: conceptual applications to frame systems, as well as floor-to-seismic resisting system connection (Jensen et al. 2006) are planned or under investigation as part of a more broad feasibility study of the proposed approach.

2 SEISMIC VULNERABILITY AND RETROFIT OPTIONS FOR EXISTING BUILDINGS

Previous earthquakes have highlighted the poor performance of existing reinforced concrete structures and the need for appropriate retrofit techniques. Figure 1 shows two examples of a shear failure in a reinforced concrete wall due to inadequate transverse reinforcement. Existing buildings may require seismic retrofitting for a number of reasons which include: poor reinforcement detailing, increased loads, revision of design codes, inadequate design philosophy (i.e. lack of capacity design principles).



Figure 1: Shear failure of a R.C. due to insufficient transverse reinforcement; a) Bolu (Turkey 1999), b) Bingol (Turkey 2003).

As part of the investigation, a literature review has been carried out to determine typical reinforcement detailing in existing structural walls that require retrofitting to highlight the likely behaviour and to ensure that an appropriate retrofit solution is adopted. It was confirmed that in New Zealand plain round reinforcing bars were used up to the mid 1960s (Liu and Park 2001), and typically a straight lap of about 40 bar diameters was used. It can also be expected that the lap will have insufficient strength to allow the full flexural capacity of the wall to develop and this will cause a bond failure in the lap under seismic excitation. This could be beneficial in saving the wall from significant damage as it will be able to rock, but in turn this could lead to a global failure of the structure. The change to the use of deformed reinforcing bars in the mid 1960s will help increase the capacity of the lap region and as a result the lap is less likely to govern the overall behaviour of the wall. Due to this it is likely that, due

to the formation of a plastic hinge, a wall using deformed reinforcement might suffer more damage under seismic response than a wall using plain round reinforcement. On the other hand, the higher strength, stiffness and dissipation capacity developed by using deformed bars should reduce the overall displacement demand of the system.

2.1 Alternative Retrofit Techniques Available

A variety of retrofit strategies for structural walls have been implemented and are available, the most common being concrete jacketing or the use of a shotcrete overlay. These two techniques are conceptually similar, since they involve adding additional reinforcement and a layer of new concrete around the existing wall (a main technological difference being that shotcrete is a form of sprayed concrete (Sabnis et al. 1996)). They result in an effective means for increasing strength, stiffness and ductility but there are several drawbacks, which include: a) need for costly foundation upgrades due to the strength increase; b) higher forces being attracted by the increase in stiffness; c) uncertainty between bond of new and existing concrete; d) labour intensive, time consuming and disruptive type of intervention.

Recent research has been carried out on the development of selective retrofit techniques which aim to offer independent upgrades in strength, stiffness or ductility (Elnashai 1992, Elnashai and Pinho 1998 and Pinho (1999)). Selective upgrading offers higher control of the seismic response as the retrofit is directly targeted at upgrading specific characteristics of the wall. The retrofit solutions are largely non complex and consist of placement of steel plates, brackets or external tendons/bars reinforcement. Figure 2 shows a series of examples of selective retrofit techniques and the effects on the force displacement response. Figure 2 (a) show a selective flexural strength upgrade, which is achieved by the addition of external reinforcement, a key aspect to achieve a selective flexural strength upgrade is to ensure that the pre-yield behaviour is not affected. This is achieved by the inclusion of a mechanical connector that acts as a delay mechanism, which ensures that the new reinforcement does not take affect until after the wall has yielded; the delay mechanism can be as simple as a slotted connection. Figure 2 (b) shows a selective stiffness upgrade which is achieved by bonding steel plates to the wall across the plastic hinge region. The walls flexural strength is not increased by this intervention as the critical plane between the wall and foundation is not crossed by the steel plates. Figure 2 (c) shows a selective ductility upgrade which is achieved by applying U-shaped steel brackets on the wall edges with a through bolt to close the bracket. The ductility intervention works by increasing the level of confinement at the wall edges.

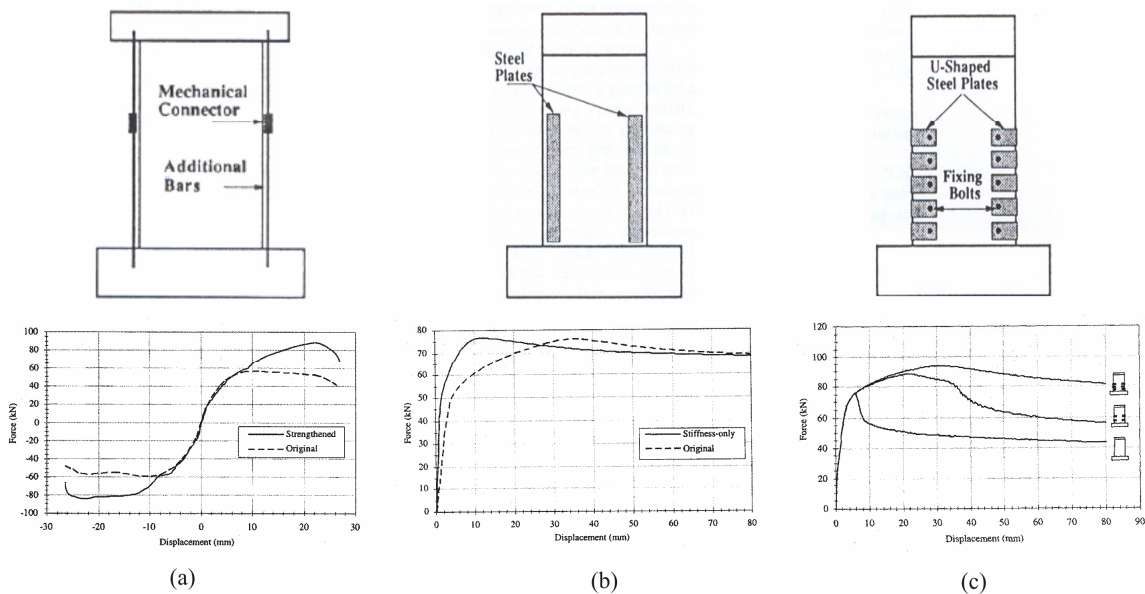


Figure 2: Basics of selective retrofit approaches:

a) Strength-only, b) stiffness-only, c) ductility-only (Elnashai 1992, Elnashai and Pinho, 1998)

3 THE CONCEPT OF SELECTIVE WEAKENING

Current seismic retrofit strategies generally focus on increasing capacity of individual elements or of the entire structure. A disadvantage of this existing approach is that it tends to lead to an increased demand on the structure as a result of the increased strength and stiffness. A selective weakening approach is herein being investigated/developed as it is believed that in some situations an initial strategic weakening of a structure will be a more appropriate option for achieving a successful seismic retrofit. Also by using selective weakening capacity design principles can be introduced to an existing structure that does not already exhibit them and a retrofit solution that results in minimal damage after a seismic response can be implemented. Acceptance of a “selective material removal” as a possible retrofit approach can be found in FEMA-273 (1997) and FEMA-356 (2000) documents. Preliminary suggestions in these documents included severing longitudinal reinforcement to change the response from a non-ductile mode to a more ductile mode or to segment walls to change their strength and stiffness.

The major advantages of using a complete selective weakening approach as proposed in this contribution for the seismic retrofit of structural walls include: a) reduce/control the demand on the foundation by controlling the capacity of the wall/s b) avoid the potential for buckling of longitudinal bars (by cutting them at the base) due to the large transverse reinforcement spacing in older building construction practice; c) introduce capacity design with the aim to improve the inelastic mechanism (e.g. from shear to flexure); d) reduce the damage connected with the development of a plastic hinge region, by enabling a controlled rocking motion to occur; e) further enhancing the response of the system by introduce a self-centring behaviour (i.e. no residual displacements) through vertical post-tensioning tendons as well as additional energy dissipation capacity through external mild steel or devices

Figure 3 shows the expected behaviour of an existing structural wall and different phases/options for a selective weakening retrofit. Figure 3 (a) shows the existing monolithic wall which is governed by a shear dominated inelastic mechanism as can be seen from the hysteretic response. Figure 3 (b) shows phase one of selective weakening which is termed “partial selective weakening” and two possible options for it application. The first option wall b’ involves vertically splitting the wall, this changes the inelastic mechanism from shear to flexure but due to the large spacing of transverse reinforcement in the existing wall, bar buckling effects are expected in the hysteretic response. Material damage will also naturally develop in the plastic hinge region depending on the type of reinforcement and bond conditions (i.e. deformed or plain round bars, lap splices etc.) The second partial selective weakening option wall b’’ involves a horizontal cut at foundation which will result in a rocking and re-centring behaviour.

Figure 3 (c) shows the second phase which is a full selective weakening, the term “full selective weakening” relates to a complete retrofit solution being developed that targets a specific level of strength/stiffness after an actual weakening intervention. A full selective weakening may therefore involve initially splitting the wall vertically and cutting it horizontally at foundation level, but then, in a second phase, introducing post-tensioning, energy dissipation devices or implementing other currently available retrofit techniques to re-enhance the properties of the structure to a target level. This may result in a retrofitted wall of equal or greater stiffness/strength/ductility than the original wall. Similarly, when protection from excessive seismic demand to other element (i.e. foundation) is a concern, the fully weakening intervention might target a level of strength lower than the original as-built solution. Wall (c’) shows a wall that has been split vertically, cut horizontally at foundation level and un-bonded post-tensioning has also been introduced to control the rocking behaviour and increase the strength. The resulting hysteretic response is bilinear elastic which ensures a self-centring behaviour. Wall c’’ has the basic properties of the wall c’ with the addition of energy dissipation devices to increase both strength and dissipation capacity. As a result a “flag shaped” hysteresis, typical of recently developed high-performance seismic resisting systems based on ductile jointed (hybrid) connections (Priestley et al., 1999; fib 2004; Pampanin 2005a).

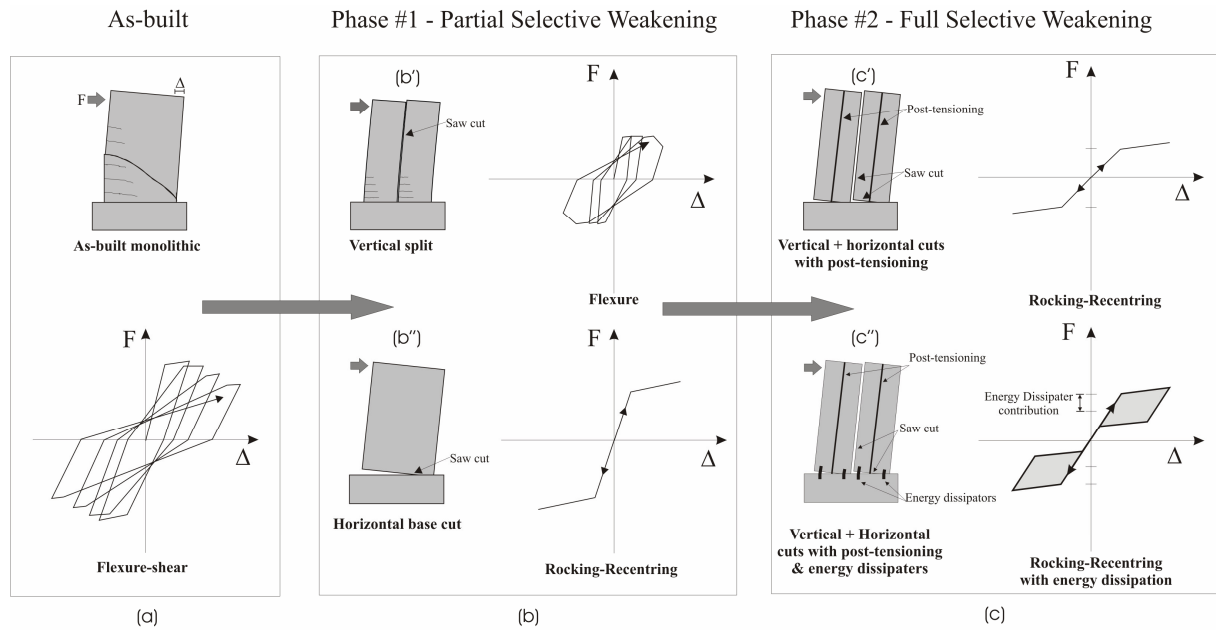


Figure 3: Expected damage and hysteresis structural response before and after intermediate phases of the retrofit intervention: (a) as-built wall; (b) partial selective weakening; (c) full selective weakening

3.1 Modification to the demand-capacity balance within a selective weakening approach

It is counter intuitive to think that by weakening a structure the seismic performance can be improved but this can result by a change in the inelastic mechanism or by a reduction in demand resulting from weakening. Selective weakening focuses on strategically altering the structural properties which will involve initially weakening the wall and then the possible option of upgrading the wall to meet a targeted performance limit. The targeted performance level may be weaker, similar or stronger than the original wall. An advantage resulting from weakening is that the demand on the wall is lowered as the strength/stiffness decreases. Demand on a structure as a result of seismic excitation is commonly expressed in terms of spectral acceleration which is usually found from design code acceleration spectra, by using a selective weakening approach that results in reduced strength/stiffness the natural period of vibration of the structure increases which in turn leads to a reduced demand.

When an as-built monolithic wall (Fig. 3a) is partially selectively weakened by a vertical split (Fig. 3 b'), this results in a stiffness of the two wall system that is about a quarter of the as-built wall and the natural period that is approximately double. A common property of acceleration spectra such as that found in NZS 1170.5 is that after 0.4 sec there is a steady reduction in the spectral acceleration. The resulting effect of increasing the natural period is that the demand significantly reduces as can be seen in Figure 4. The reduction in demand can also be aided by a change in the inelastic mechanism which allows a higher level of ductility to be achieved, which in turn increases the level of damping and further lowers the spectral acceleration. A side effect of the reduced strength/stiffness and increased natural period that results from selective weakening is that the spectral displacement is increased. This can be seen in Figure 4 in terms of a displacement spectrum. A increase in damping due to a changing the inelastic mechanism can help to reduce the spectral displacement but also as a trade-off wall designs are commonly governed by minimum reinforcement requirements to resist temperature and shrinkage effects. This means that they will have a stiffness/strength in excess of that required so after selective weakening the displacements may still be within acceptable levels. Selective weakening will not always result in an overall weakening of the wall system, when "full selective weakening" is used a target performance level can be set to ensure that there is no demand increase or to control the level of demand increase.

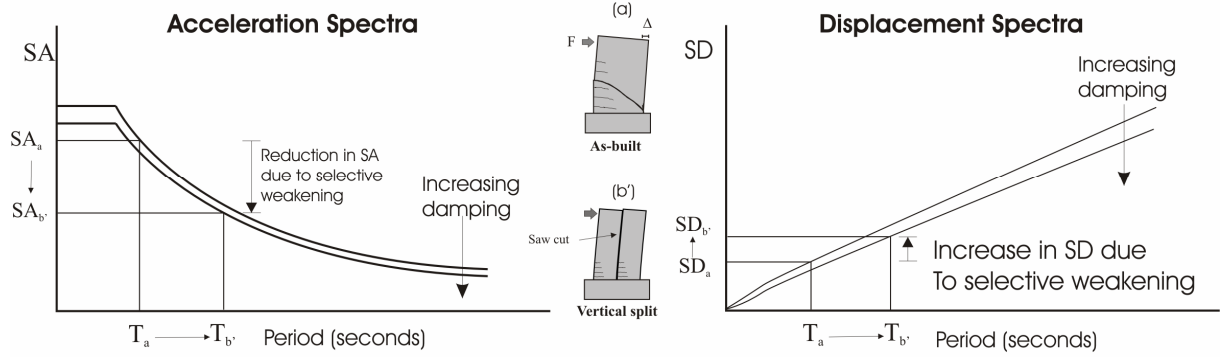


Figure 4: The effect of partial selective weakening on spectral acceleration and displacement demand

Figure 5 shows two possible examples of how selective weakening can be used for the capacity re-design of a wall and foundation system. Figure 5a shows force displacement responses for the as-built wall, a wall retrofitted by a conventional technique and a wall retrofitted by partial selective weakening. The as-built wall is governed by a shear dominated inelastic mechanism and a conventional retrofit technique formed using FRP wrapping is used as the conventional retrofit technique but this can increase the wall's capacity so that the wall is stronger than the foundation. Wall b' is partially selectively weakened by a vertical split which results in a flexural inelastic mechanism developing in the wall and a wall with a capacity less than that of the foundation.

Figure 5b shows the force displacement response of the as-built wall which is governed by a shear dominated inelastic mechanism and two possible retrofit options using full selective weakening. Wall c' is selectively weakened by vertically splitting the wall, cutting it at foundation level and adding post-tensioning. This results in a rocking and re-centring behaviour with a lower strength than the as-built wall and the foundation. Wall c'' is the same as wall c' except that energy dissipaters have been added and the post-tensioning force has been increased. In this case a full selective weakening technique is used that targets a strength higher than the as-built wall but lower than the foundation capacity.

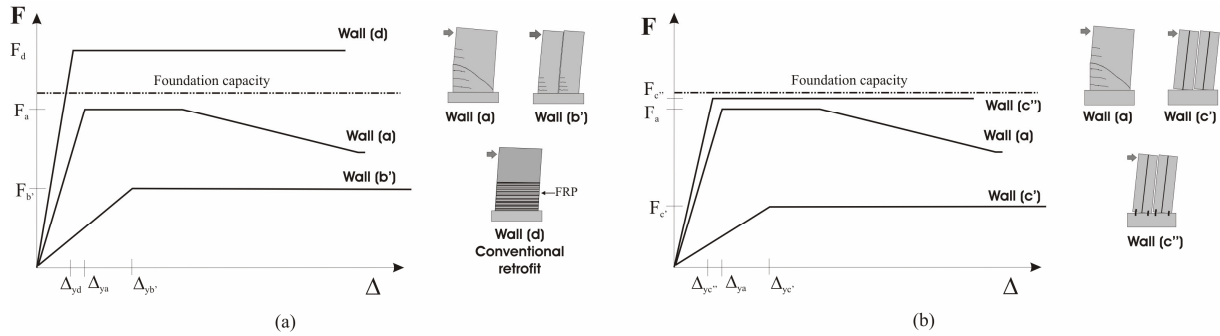


Figure 5: Selective weakening capacity design examples

4 IMPLEMENTATION OF SELECTIVE WEAKENING

As mentioned earlier the initial investigations into selective weakening will focus on implementing it for structural wall buildings, this will involve strategically saw cutting the walls vertically and/or horizontally. Horizontal saw cuts at foundation level will be used to sever longitudinal reinforcement to allow for rocking type behaviour while vertical saw cutting will be used to segment the wall into portions with a lower moment capacity and lower the chance of a shear dominated inelastic mechanism. But cutting the walls introduces a series of new issues that need to be considered and overcome to achieve a successful retrofit. Major problems introduced and possible simple solutions are: a) segmenting a wall by a vertical cut will involve cutting through the transverse reinforcement, a solution to reintroduce confinement and shear capacity such as FRP wrapping or steel confining plates will be needed; b) A horizontal cut at foundation level will sever the longitudinal reinforcement,

therefore a solution to increase the moment capacity and energy dissipation will be needed, this could include post-tensioning and damping devices; c) A horizontal cut could result in the wall sliding on the cut region therefore a mechanical shear key will be required; d) The interaction between the wall and floor diaphragm need to be considered.

5 EXPERIMENTAL INVESTIGATIONS

To validate selective weakening as a viable retrofit strategy a series of experimental investigations are being performed in the Civil engineering laboratory at the University of Canterbury. The experiments are being performed on 2/3 scale rectangular cantilever wall specimens with reinforcement details typical of those found in existing buildings. The experimental investigations also serve as a means of confirming analytical predictions, highlighting problems to overcome and are a chance to test which other currently available retrofit techniques are best suited for use in conjunction with selective weakening.

The first phase of experiments will be in relation to existing walls with plain round reinforcing bars and a straight lap detail. A control specimen will be tested and then a second wall with the same reinforcing details will be selectively weakened. As it is thought that the lap detail will govern the inelastic behaviour, selective weakening will be performed by horizontally cutting it at foundation level which will allow the wall to rock. Figure 6 below shows the reinforcement details of the first wall in the experimental program.

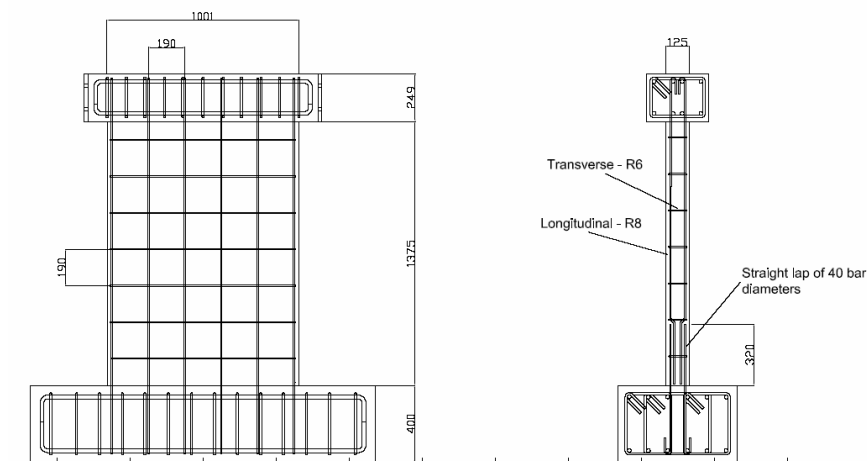


Figure 6: Experimental specimen with plain round reinforcing bars and a straight lap detail.

The second phase of experimental investigations is going to be performed on a wall with deformed reinforcement and a lap detail that does not govern the inelastic behaviour. A control specimen will be tested and then on a second specimen selective weakening will be performed by vertically cutting the wall into two segments.

6 CONCLUSIONS

In this contribution a preliminary feasibility study for the development of selective weakening as a seismic retrofit strategy for reinforced concrete structural walls has been outlined. Current retrofit strategies generally focus on increasing capacity but in certain situations a reduction in strength or weakening may be more appropriate. One of the major advantages is the ability to introduce capacity design to existing structures that do not already exhibit it. By selective weakening capacity design is not only limited to ensure that a flexure dominated inelastic mechanism is achieved before a shear dominated inelastic mechanism forms. Further, the design process can be comprehensive by ensuring that the foundation capacity is not exceeded. Selective weakening can also be used to implement recent technological developments in building systems. Such systems commonly utilise rocking behaviour to ensure minimal damage and a self-centring behaviour so that there are no residual displacements after seismic response.

Initial experimental investigations are on-going in the Civil Engineering laboratory at the University of Canterbury, which consist of 2/3 scale reinforced concrete walls with similar reinforcement details to those found in existing pre-1970s buildings in New Zealand.

ACKNOWLEDGEMENTS

The financial support provided by the NZ Foundation of Science and Technology through the FRST-Research Program “Retrofit Solutions for NZ” is gratefully acknowledged.

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